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THE EVOLUTION OF SPACE MECHANISMS IN THE ESA R&D PROGRAM

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INTRODUCTION

The evolution of space mechanisms is presently occurring very quickly in Europe, being driven by vigorous new programs in the area of Scientific Satellites, Columbus space station development, applications spacecraft for communications, Earth observation and meteorology, and the Ariane V and Hermes space transportation systems.

In this paper the status of recently completed and already ongoing technology developments will be discussed as well as some of the most important future developments. A selection will be made since the number of developments is rather large, but the aim will be to consider the applications or lessons learned from the technology programs and the application goals of the new areas.

SPACE MECHANISMS TECHNOLOGY IN THE ESA PROGRAM

The word mechanism tends to cover a wide range of items and disciplines, so Figure 1 has been evolved to give a classification of the disciplines involved. Based on this classification, the mechanism technology items included in the Agency's program for 1988 have been listed by category in Table 1.

A number of items which were already reported in 1985 [1] have been completed or are about to be finished and these will be considered first in order to determine the outcome of the technology work.

Finally, the new items will be described in order to determine the future direction of the mechanisms technology which is being developed.

EVOLUTION OF SPACE MECHANISMS TECHNOLOGY IN RECENT YEARS

Category 1 Electromechanical Components

There is continuous support of the development of electric motors for space use within the ESA technology program, since there is always a demand for special application devices. Of particular interest in this respect has been a superconducting motor for cryogenic use.

Support for this work commenced in 1981 and by the end of 1984 a superconducting motor, suitable for operation of scientific instruments in the

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focal plane of a cooled telescope for example, had been developed and tested by SEP and SAGEM in France. An already space-qualified size-stepper motor was used and the winding material changed to a niobium-titanium alloy. A heat dissipation of below 1 mW during operation was achieved. Testing included vibration and torque measurement at cryogenic temperature, together with an endurance test at liquid helium temperature [2].

This technology has been successfully transferred since the motor is being used as a component of the infra-red camera on the Infrared Space Observatory (ISO) project of ESA. A continuation technology study has recently been completed, the aim being to reduce the overall heat dissipation of such a motor including its lead wires.

A second example of recently completed motor technology is the so-called Digital Position Actuator (DPA). This has been less successful in terms of application, since no specific need has arisen. The development was based on a perceived need rather than an "external" interest or inquiry. The aim has been to develop a motor capable of indexing to a specific angular position on receipt of a digital command. Supposed application was in scientific instruments and/or robotics. An interesting feature was the strict packaging dimensions which were specified to house both motor and electronics. This was initially achieved by the contractor (Inland Motor Co., Ireland), but the electronics was rejected since not all were space approved. When space-approved devices were used, the dimensions could not be reached. The final dimensions achieved were 85-mm square cross-section by 190-cm long compared with a requirement of 70-mm diameter by 100-mm long. The motor developed was a dc brushless motor with trapezoidal motor flux distribution. It has the capability of indexing to a given angle (or series of angles) with an accuracy of 10 arcsec.

Category 2 Control Actuators

Category 2 considers Energy Storage Wheels (ESW) and reaction and momentum wheels.

In the case of ESWs, an increase in interest in these devices occurred in 1984, mainly because of the perceived possibility of using them in space station elements to replace batteries. A workshop to review the technology was held at NASA [3], and following this, in Europe new work was started on rotor development for an ESW suitable for space use.

The design and manufacture of such a rotor was completed at the end of 1986 under an ESA technology contract. The rotor consists of a hub made of high strength aluminum alloy with four spokes and an integral (thin) ring. The rim consists of carbon fiber cylinders mounted with interference fit to this ring. The carbon fiber rim concept enables a high energy density to be achieved, but still enabling the mass, volume, and diameter to be restricted. Both 2D and 3D stress analyses have been performed using the finite element approach. The octant model used for 3D analysis is shown in Figure 2; and the mechanical and functional characteristics are given in Table 2.

For the time being, interest in these devices has again lessened, and the first generation European Space Station (Columbus) will certainly use batteries. An extension contract to complete some testing of the rotor is planned for the near future, and then it seems that this technology will again become dormant until such time as project interest arises in it.

Category 3 Antenna and Instrument Mechanisms

This category covers a relatively wide range of items, which have no logical grouping characteristics in terms of mechanical function.

A particularly interesting device is the high-precision displacement mechanism. This has been under technology development for some time (since 1984) and is designed to actuate folding antenna panels on a sub-millimeter spaceborne radio telescope, with an accuracy approaching 1 micron. Two concepts for such a mechanism have been studied by Dornier (Germany) and Sener (Spain). The initial concept was a type of 3D leverage system with motion reduction via flexural members. A mock-up of this device was built and successfully tested under ambient conditions. A drawing of this device is shown in Figure 3A. Potential problems in the area of materials, thermal performance, and integration, however, led to the definition of a second device, shown in Figure 3B. Movement is caused by distortion of a flexural ring and this device has also been successfully tested under ambient conditions. Some further refinement of this design is necessary (e.g., in terms of reduction of high stresses) and it is intended to manufacture a space-approved version and perform thermal-vacuum testing in order to complete the technology development.

Another device of interest in this category is the so-called micro-gravity isolation mount (MGIM). This is a magnetically suspended, 6-degree-of-freedom platform on which experiments can be mounted. The suspension is activated by a positive feedback system causing the experiments to be isolated from external vibration disturbances in the frequency range of interest. The feasibility of this device has already been demonstrated under an ESA contract running from October 1985 to February 1987. The results of this work were presented at the 21st Aerospace Mechanisms Symposium at Houston. The interest in this work for space station application is continuing and a further contract was awarded in September 1988 in order to study the development of this device for mounting inside an experiment on the Columbus space station.

Category 4 Deployment Mechanisms

The only item presently included in this category is the coilable tube mast (CTM). A small diameter version has already been built by the SENER company in Spain and will fly on the Ulysses spacecraft. The latest version of the boom is shown in Figure 4, where the shape of the boom cross-section is also visible. The mechanism is capable of deploying and retracting the boom which has nominal length of 15 m. The initial development was completed in April 1988 with the achievement of the following:

1. Design and manufacture of a CTM with deployment/retraction capability

2. Manufacture of several tube samples in beryllium copper and carbon fiber reinforced plastic

3. Demonstration of continuous manufacturing methods for both tube materials

4. Functional life and vibration testing of the complete CTM. During life testing, 20 cycles of deployment and retraction were completed with full success, with no detectable damage occurring.

A new contract has been started on the CTM in order to obtain a qualified version with fully space-approved parts and components. Under this same contract, a qualification approach for a family of tube sizes, covering the diameter range of approximately 22 mm to 130 mm, will also be evolved.

It is also encouraging to note that this technology is being applied in another new area, namely to deploy an in-flight contamination experiment on the Shuttle under a cooperative U.S./European venture on the Technology Demonstration Program. The payload, which weighs 15 kg, is supplied by NASA, and ESA will supply the CTM. This will be a 15-m long retractable version with a cross-section diameter of approximately 63 mm, and will be ejectable for safety reasons.

The previous examples are of technology items already in a reasonably advanced, or even completed, stage of development. These examples illustrated that technology items must be continually reviewed and planned. Obviously certain items, such as the energy storage wheel and the digital positioning actuator seem to have been developed too early for direct application for project needs. The microgravity isolation mount technology, however, has been investigated largely without project support, but nevertheless subsequently raised interest especially among the scientific users community. It has also helped to raise the awareness and understanding of the microgravity phenomena and related engineering aspects.

Similarly, the CTM development has raised the interest of potential users and found application in an area which was not originally envisaged. Another deployment mechanism, the extendable and retractable mast (ERM) which was reported in Reference 7 has been successfully transferred to the Columbus project after completion of the technology work.

RECENT TECHNOLOGY

This section considers some of the newer items under investigation and indicates their expected applications.

The large momentum wheel work started at the end of 1984 with the Teldix company and its aim was to study momentum wheels suitable for eventual use on the Columbus Space Station. The momentum "ceiling" for the initial study was

1000 N-m-sec. In a continuation study completed at the end of 1988, a detailed design of a wheel of 1000 N-m-sec with a diameter of 60 cm (Columbus requirement) was completed, and an engineering model was built and tested. Prior to this work, no wheel above 70 N-m-sec had been built in Europe. The particular design challenges posed by this development can be summarized as follows:

- High centrifugal forces, 15 times higher than for previous wheels
- Increased vibrational loads
- Increased atmospheric loading on the housing
- Strength requirements approaching the limits of existing materials.

The final wheel design consisted of a steel rim held to a central ball bearing hub by five bolted spokes inclined by 8 deg. The nominal operating speed is 6000 rpm. A cross-sectional drawing of this wheel is shown in Figure 5.

At the present time the wheel momentum requirements for Columbus seem to be more in the region of 300 N-m-sec. The development of a 1000 N-m-sec wheel has been justified, however, from a technology point of view, since the higher requirements were a development driver. The problems overcome in developing a 1000 N-m-sec wheel enable the smaller (medium) wheel to be now developed much more easily.

Two technology studies have recently commenced in the mechanical systems category which are directly related to the Agency's Scientific Satellite Program.

The first one, Sample Acquisition Systems, is being undertaken to support the Comet Nucleus Sample Return mission (CNSR, now known as ROSETTA). In terms of mechanisms, this is an extremely challenging mission and the following are being studied in the technology work:

- Cometary soil properties
- Anchoring of the spacecraft to the comet surface
- Drilling of core samples
- Sampling of surface material
- "Harpooning" of the comet surface.

The initial study commenced in March 1988 with Tecnospazio and Tecnomare of Italy. A survey of possible cometary material properties was first carried out. Following this, a conceptual and trade-off phase on the mechanism design was completed. Baseline mechanisms have been chosen and will be designed in

detail in the final part of the study work. The baseline mechanisms chosen are shown in Figure 6. Of these, the most challenging is certainly the drill system. Core samples have to be extracted and then stored in sealed containers for return to Earth laboratories. The sampling requirements for this instrument are as follows:

Core sample
- sample depth - 1 m required with goal of 3 m
- sample diameter - 0.06 to 0.14 m

Volatile sample
- depth - 0.2 m below core sample
- volume - 15 dm^3

Crust sample
- depth - 0.05 m
- volume - 4 dm^3.

Following the completion of the design study, it is planned to initiate a new contract in order to manufacture and test prototype mechanisms.

The second technology study is for the Spin and Eject Mechanism to be used on the Cassini mission. This is a joint ESA/NASA mission. The "mother" spacecraft provided by NASA will orbit Saturn, whereas, ESA will provide a probe for landing on Titan, one of Saturn's moons. The cruise phase from Earth to Titan will have a duration of approximately 8 years and then the mechanism will eject the probe with a velocity of 0.3 m/sec relative to the Orbiter and with a spin rate of 10 rpm.

A contract to study this mechanism was started with the Piaggio company of Italy in May 1987. Design, dynamic analyses and finally a trade-off of several candidate mechanisms has been performed, leading to a choice of preferred mechanism. A detailed design and analysis of this will be made and then a mock-up of the device will be built and tested. The test will simulate the zero-g condition together with the probe inertia about the spin axis, which is 50 kg m^2. The expected probe mass for the Cassini mission is 192 kg. The chosen mechanism consists of a movable ring, used to eject the probe, which is pushed in a track of 30 deg inclination by four compression springs. The probe is released from the moveable ring by pyrotechnics for "launch." The Ring diameter is 0.5 m. A drawing of this mechanism is shown in Figure 7.

The remaining items in Table 1 will not be discussed in any detail since they are being negotiated and have not yet started. They are, however, of interest and the following short comments can be made.

The tether mechanism study will survey possible European tether missions and then lead to designs of various suitable tether mechanisms, followed by manufacture and testing of the most technologically challenging parts of these mechanisms.

In category 3, antenna deployment and pointing mechanisms will be studied for the next generation of European communication spacecraft, specifically the Data Relay Satellite, meant for communicating with the Columbus Space Station, and the experimental spacecraft known as SAT2. There is a high interest in Europe in antenna pointing mechanisms and the development of such a device for large angles has taken place under the ESA technology program. This is known as the Hemispherical Pointing Mechanism (HPM) and was mentioned in Reference 1. The design was based on an inclined wedge principle. An engineering model of a single axis drive unit has been developed and is planned to be thermal vacuum tested during 1989. There is presently project interest in this device for possible use in pointing a laser communication experiment.

Another category of interest is tribology, but this aspect needs a paper to itself and thus can only be touched upon here. At the time of writing, a new four-year contract for research into space tribology is being negotiated with the European Space Tribology Laboratory (ESTL). This contract will cover, in particular, the aspects listed below which are all aimed toward solving particular new project related problems.

1. High speed bearing lubrication
2. Slip ring lifetime improvement
3. Gearbox lubrication especially for robotics
4. Cryogenic tribology
5. High temperature tribology
6. Continuing fundamental investigations of space lubricants, especially MoS_2 and ceramics.

Further tribological studies listed in Table 1 are directed towards improvement in understanding the problems related to turbomachinery.

CONCLUSIONS

The evolution of space mechanisms in terms of increasing complexity and size is continuing. Spacecraft projects are finding increasingly more challenging roles for mechanisms and the technology work is being directed toward solving the problems raised.

In general, the high interest and support in the mechanisms technology development program could be said to be related to the relatively high success in both utilizing and directing the work for projects. Close liaison and careful planning therefore pays dividends in this respect. Nevertheless, It must be remembered that technology by its very nature explores relatively unknown areas, therefore not all lines of inquiry can be expected to lead to immediate applications. In this respect, it is important to retain

flexibility so that work can be re-directed or stopped if necessary. The lessons learned should then be utilized for further work.

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TABLE 1. MECHANISMS TECHNOLOGY BY CATEGORY

1. Electro-mechanical	• Electric motors components • Turbomachinery rotor dynamics
2. Control Actuators	• Large momentum wheel • Rotors for ESW's
3. Instrument and antenna mechanisms	• High precision displacement mechanism • Microgravity isolation mount • Antenna deployment and pointing
4. Deployment mechanisms	• Collapsible tube mast
5. Mechanical Systems	• Sample acquisition systems • Spin/eject devices for planetary mission • Tether mechanism
6. Tribology	• Tribology • Seal material life test • Advanced seal technology • Advanced bearing technology

TABLE 2. ESW MECHANICAL AND FUNCTIONAL CHARACTERISTICS

• Outer diameter	600 mm
• Inner diameter (of composite rim)	510 mm
• Width	340 mm
• Outer diameter growth at maximum operating speed 24,000 rpm	2.8 mm
• Mass	60.5 kg
• Max-operating peripheral speed	770 m/sec (corresponding to 2566 r/sec angular velocity
• Energy density at maximum operating speed	3.3 KWh

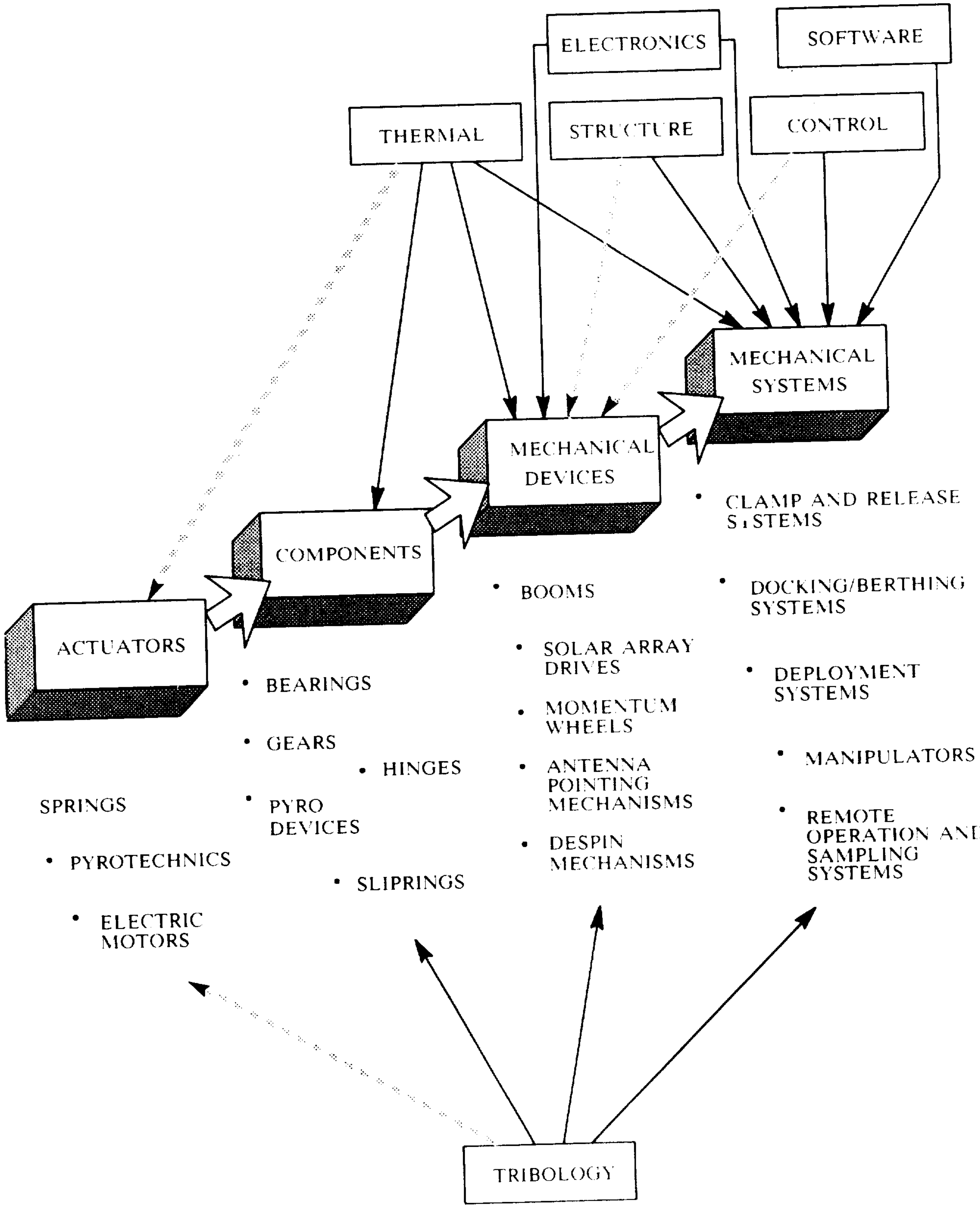


Figure 1. Mechanisms hierarchy.

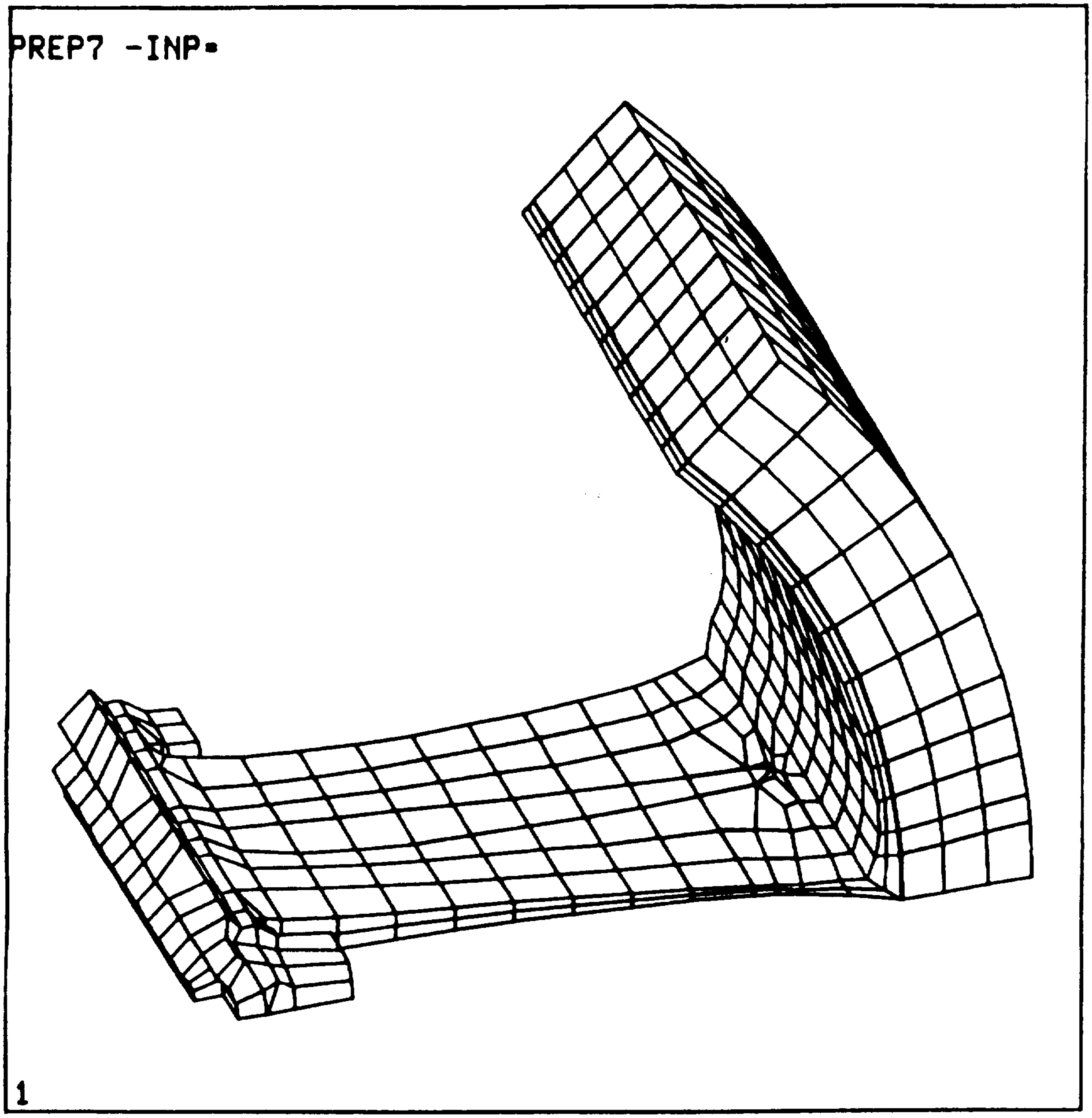


Figure 2. Three-dimensional model of flywheel.

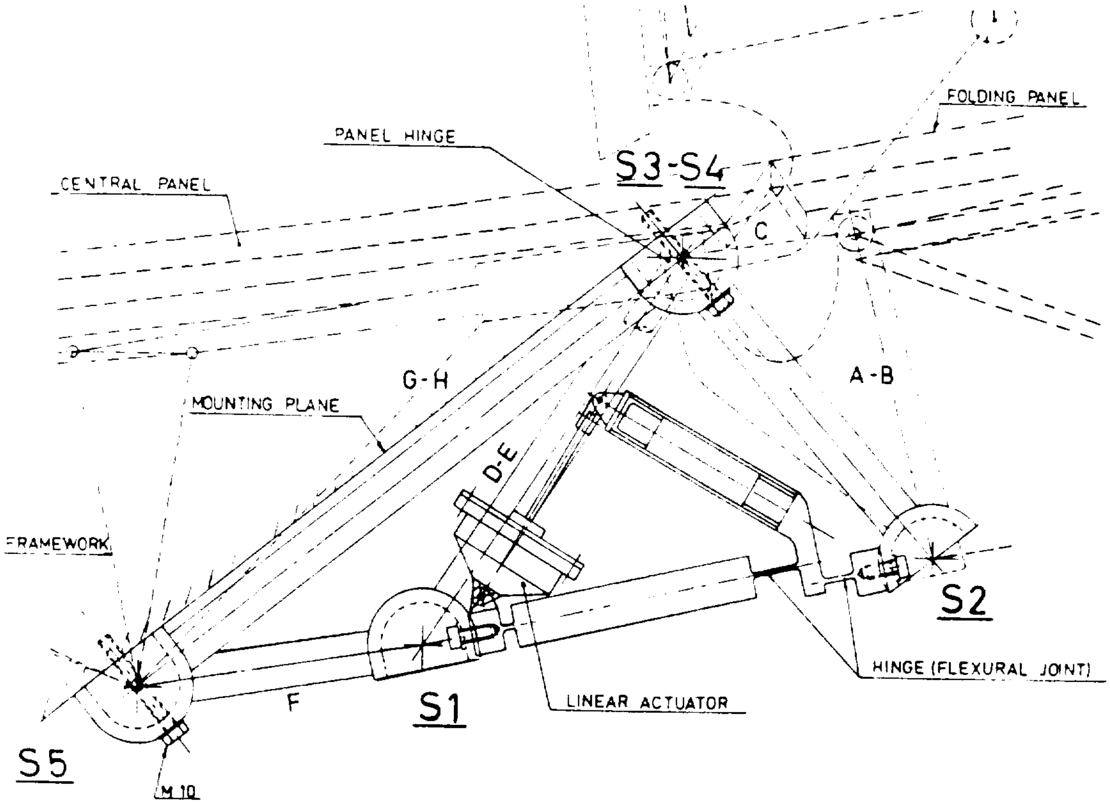


Figure 3A. Precision actuator type I.

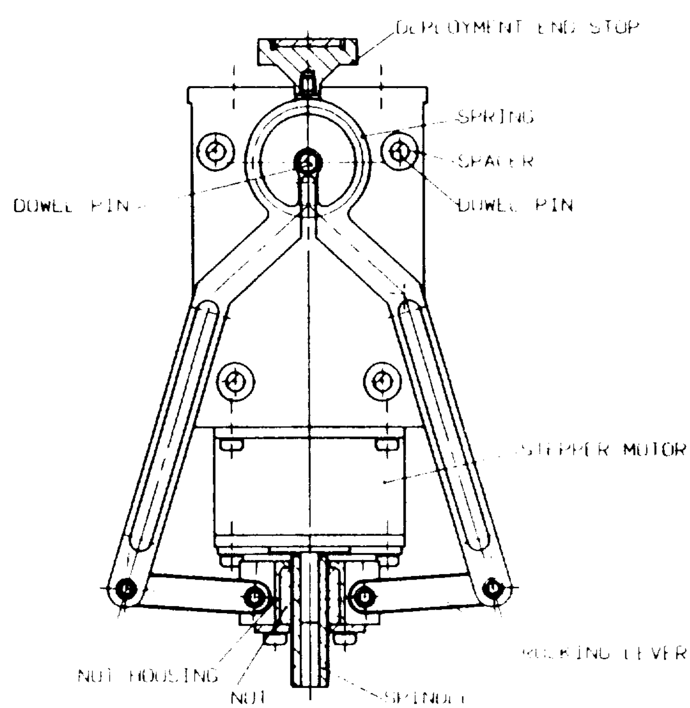
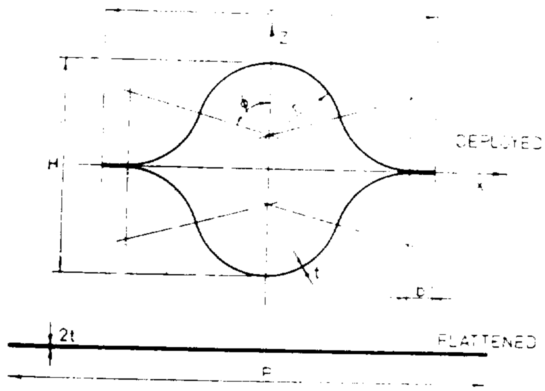


Figure 3B. Precision actuator type II.



Tube cross-section

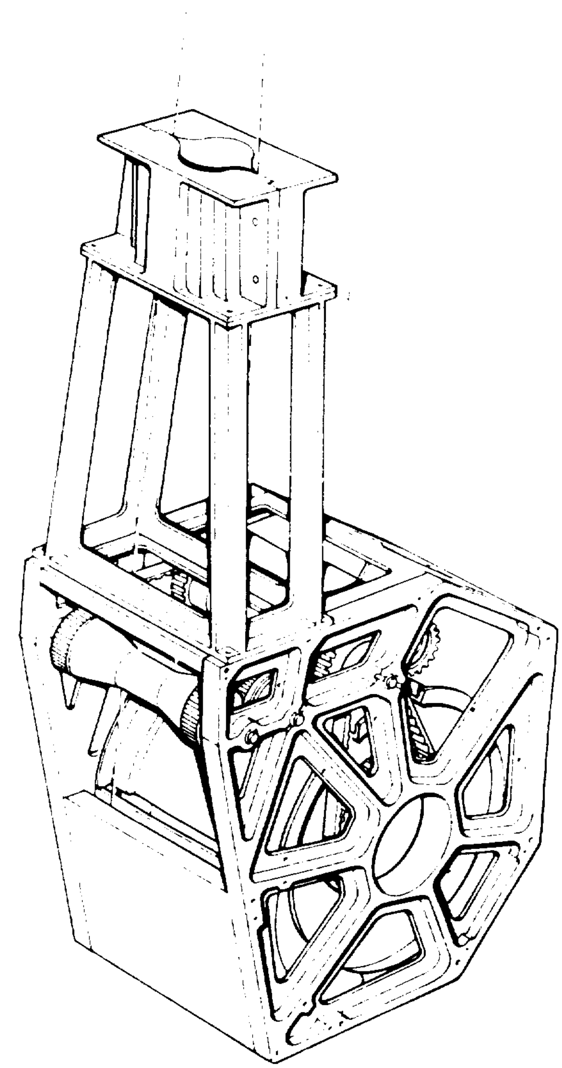


Figure 4. Coiled tubular mast.

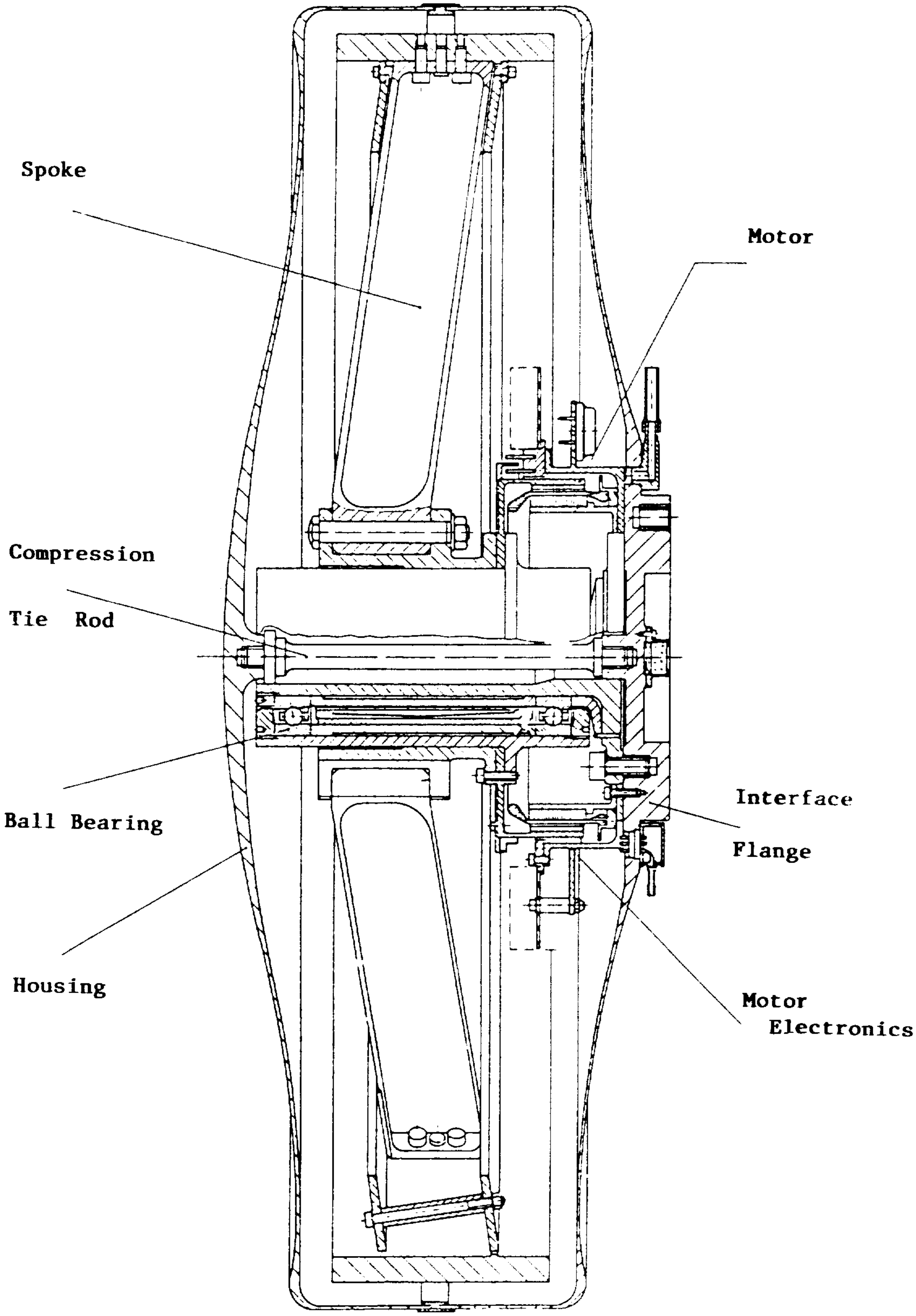


Figure 5. Large reaction wheel.

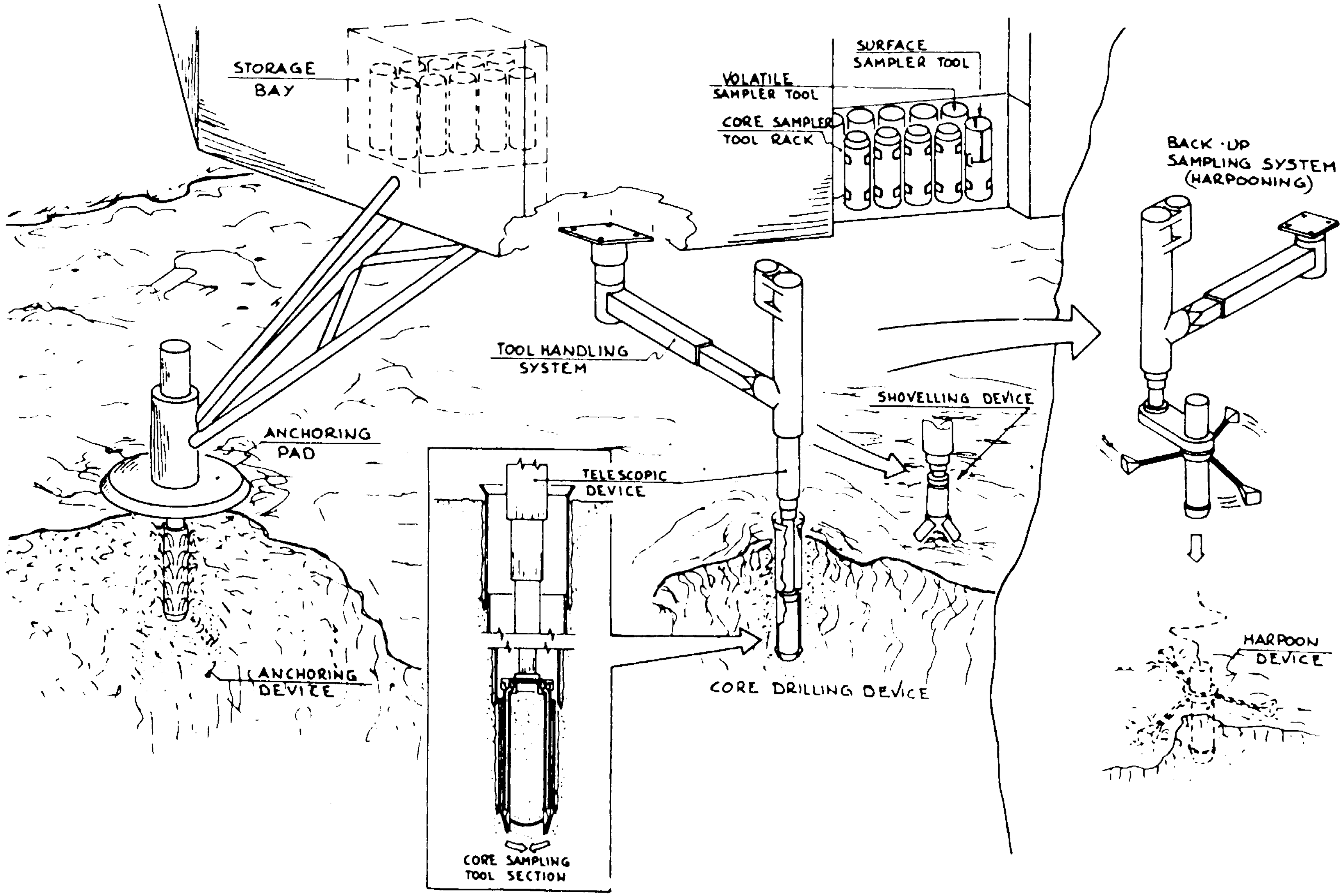


Figure 6. Comet surface sampling mechanisms.

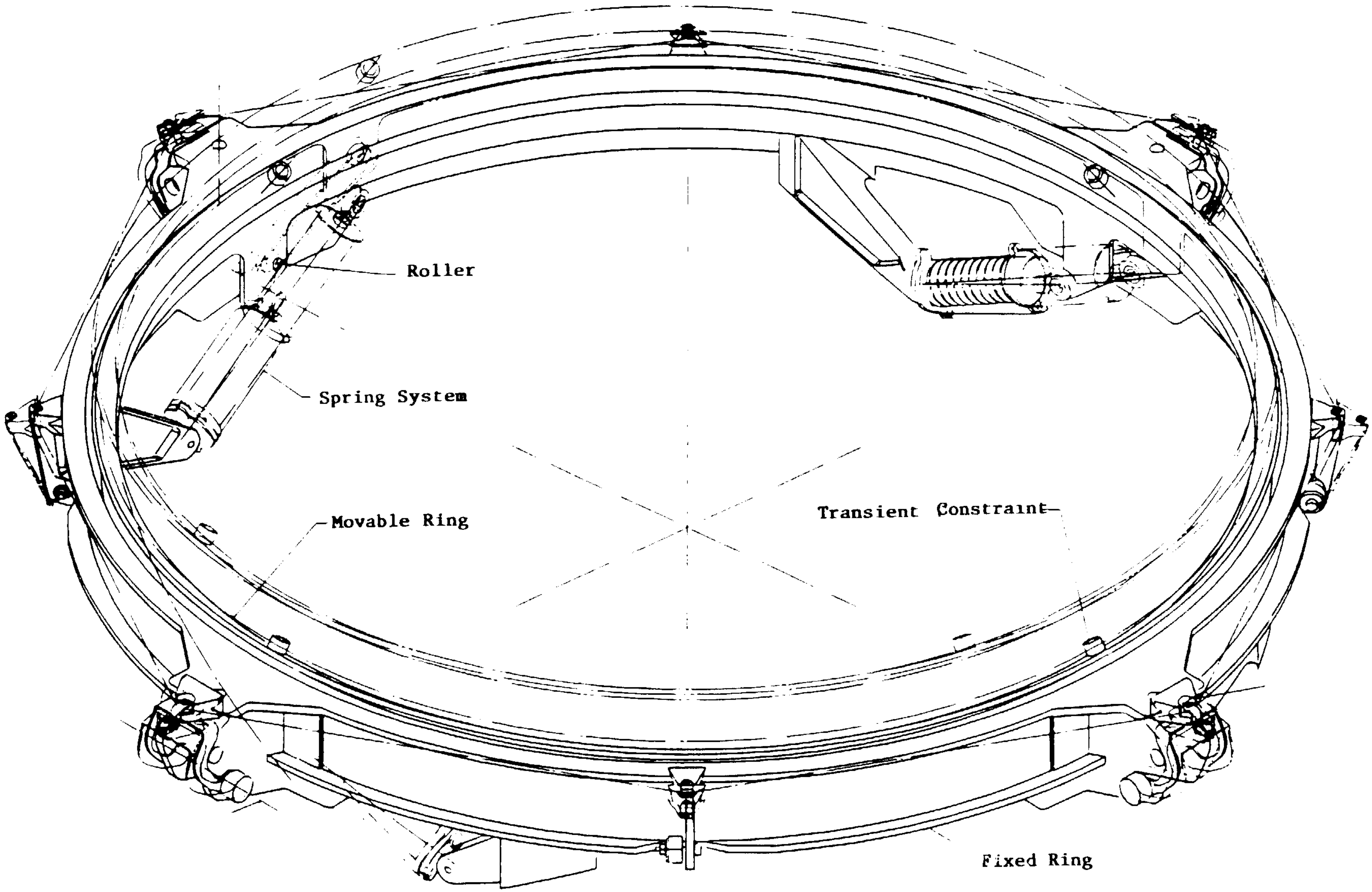


Figure 7. Spin/eject mechanism.